Summary of Research

Title: Synthesis Methods for Robust Passification and Control

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Preface

This report provides a concluding summary of the research work performed over the duration 6/00-11/00 for the co-operative research agreement NCC-1-348 between NASA Langley Research Center and Kansas State University. As the P.I., Dr. Atul G. Kelkar, will be moving to Iowa State University effective January 2001 the remainder of the work will be continued at the new institution.

1 Executive Summary

The research effort under this cooperative agreement has been essentially the continuation of the work from previous grants. The ongoing work has primarily focused on developing passivity-based control techniques for Linear Time-Invariant (LTI) systems. During this period, there has been a significant progress made in the area of passivity-based control of LTI systems and some preliminary results have also been obtained for nonlinear systems, as well. The prior work has addressed optimal control design for inherently passive as well as non-passive linear systems. For exploiting the robustness characteristics of passivity-based controllers the passification methodology was developed for LTI systems that are not inherently passive. Various methods of passification were first proposed in [4] and further developed in [5], [8], and [10]. In [7], the robustness of passification was addressed for multi-input multi-output (MIMO) systems for certain classes of uncertainties using frequency-domain methods. For MIMO systems, a state-space approach using Linear Matrix Inequality (LMI)-based formulation was presented in [13] for passification of non-passive LTI systems. In [8], an LMI-based robust passification technique was presented for systems with redundant actuators and sensors. The redundancy in actutors and sensors was used effectively for robust passification using the LMI formulation. The passification was designed to be robust to an interval-type uncertainties in system parameters. In [?], the passification techniques were used to design a robust controller for Benchmark Active Control Technology wing under parametric uncertainties. The results on passive nonlinear systems, however, are very limited to date. Our recent work in this area was presented in [7] wherein some stability results were obtained for passive nonlinear systems that are affine in control.

The passification methodology was validated experimentally on two different real-life test articles, namely, flexible link with piezo actuator [11] and 1-D acoustic duct pk01-j. It was demonstrated that the passivity-based controllers can provide robust stability for unmodeled dynamics and parametric uncertainties even for nonminimum systems such as these using robust passification techniques.

Several publications and conference presentations resulted from this ongoing research. The list of publications and presentations is given below.

List of Publications

[1] A. G. Kelkar and S. M. Joshi.

Control of Nonlinear Multibody Flexible Space Structures, volume 221 of *Lecture Notes in Control and Information Sciences.*

Springer-Verlag, August 1996.

[2] A. G. Kelkar and S. M. Joshi.

Global stabilization of flexible multibody spacecraft using quaternion-based nonlinear control law.

Journal of Guidance, Control, and Dynamics, 19(5):1186–1188, 1996.

[3] S. M. Joshi and A. G. Kelkar.

On longitudinal control of high speed aircraft in the presence of aeroelastic modes.

NASA Technical Memorandum, (TM-110254), 1996.

[4] S. M. Joshi and A. G. Kelkar.

Robust control of a class of passive nonlinear systems.

Technical Report TM 110287, NASA Technical Memorandum, October 1996.

[5] S. M. Joshi and A. G. Kelkar.

Inner loop control of supersonic aircraft in the presence of aeroelastic modes.

IEEE Transactions on Control System Technology, 6(6):730–739, November 1998.

[6] A. G. Kelkar and S. M. Joshi.

Robust passification and control of non-passive systems.

In *Proceedings of the American Control Conference*, pages 3133–3137, Adam's Mark Hotel, Philadelphia, PA, June 24-26 1998.

[7] A. Isidori, S. M. Joshi, and A. G. Kelkar.
Asymptotic stability of interconnected passive non-linear systems.
International Journal of Robust and Nonlinear Control, 9:261–273, 1999.

[8] S. M. Joshi and A. G. Kelkar.
Robust passification via optimal sensor blending and control allocation.
International Journal of Control (to appear, 2000.

[9] A. G. Kelkar and S. M. Joshi.
Control of bact wing via robust passification.
AIAA Journal of Guidnace Control and Dynamics (to appear), 2000.

[10] A. G. Kelkar, Y. Mao, and S. M.Joshi.
Synthesis of lq-optimal constant-gain positive-real controllers.
Control and Intelligent Systems (to appear), 2000.

[11] A.G. Kelkar and S.Rangarajan.
Modeling and control of nonlinear flexible robots.
IEEE Journal of Robotics and Automation (to be submitted), 2000.

[12] S.V.Gosavi and A. G. Kelkar.
Control of piezo-actuated flexible link.
Control and Intelligent Systems (submitted), 2000.

[13] A. G. Kelkar, Y. Mao, and S. M.Joshi.
Lmi-based passification for control of nonpassive systems.
Automatica (to be submitted).

[14] H. R. Pota and A. G. Kelkar.
Modeling and control of Acoustic Ducts.
ASME Journal of Vibration and Acoustics, to appear, January 2001.

[15] S. M. Joshi and A. G. Kelkar.

Inner loop control of supersonic aircraft in the presence of aeroelastic modes.

In *Proceedings of the IEEE Conference on Control Applications*, Dearborn, Michigan, September 15-18 1996.

[16] A. G. Kelkar and S. M. Joshi.

Trajectory tracking of multibody spacecraft.

In *Proceedings of the 1996 International Mechanical Engineering Congress and Exposition*, Atlanta, GA, November 17-22 1996.

[17] A. G. Kelkar and S. M. Joshi.

Globally stable maneuvers of flexible space robots.

In *Proceedings of the Fourth International Conference on Control, Automation, Robotics, and Vision*, volume 1, pages 167–171, Westin Stamford, Singapore, December 3-6 1996.

[18] A. G. Kelkar and S. M. Joshi.

Robust control of non-passive systems via passification.

In *Proceedings of the American Control Conference*, volume 5, pages 2657–2661, Albuquerque, NM, June 4–6 1997.

[19] S. M. Joshi and A. G. Kelkar.

Passivity-based control of elastic systems.

In *Proceedings of the International Conference on Control Applications*, Hartford, Connecticut, October 5-7 1997.

[20] A. G. Kelkar and S. M. Joshi.

On passivity-based control of flexible multibody nonlinear systems.

In *Proceedings of the IEEE Conference on Decision and Control*, pages 4862–4867, Hyatt Regency, San Diego, CA,, December 10-12 1997.

[21] A. G. Kelkar and S. M. Joshi.

Robust passification and control of non-passive systems.

In *Proceedings of the American Control Conference*, pages 3133–3137, Adam's Mark Hotel, Philadelphia, PA, June 24-26 1998.

[22] V. Kapila, A. G. Kelkar, Y. Mao, and S. M. Joshi.

Passification via dynamic feedback compensation.

In *Proceedings of the IEEE Conference on Decision and Control*, pages 3867–3869, Tampa, Florida, 16–18 December 1998.

[23] S. M. Joshi and A. G. Kelkar.

Robust passification via optimal sensor blending and control allocation.

In *Proceedings of the American Control Conference*, pages 278–282, San Diego, CA, June 2–4 1999.

[24] Y. Mao, A. G. Kelkar, and S. M. Joshi.

Synthesis of optimal constant-gain positive real controllers.

In *Proceedings of the American Control Conference*, pages 273–277, San Diego, CA, June 2–4 1999.

[25] A. G. Kelkar and S. V. Gosavi.

A concurrent design methodology for control of slewing flexible link using piezo-actuators and sensors.

In *Proceedings of the Second IASTED International Conference on Control and Applications*, pages 310–315, Banff, Canada., July 25-29 1999.

[26] S. M. Joshi, D. E. Cox, and A. G. Kelkar.

Robust control of uncertain systems via norm-bounded lqg-type controllers.

In Proceedings *American Control Conference 2000 (presented as an invited paper)*, Chicago, IL, June 28–30 2000.

[27] A. G. Kelkar, Y. Mao, and S. M. Joshi.

Lmi-based passification for control of non-passive systems.

In Proceedings *2000 American Control Conference (presented as an invited paper)*, Chicago, IL, June 28-30 2000.

List of Presentations

[1] S. M. Joshi and A. G. Kelkar.

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Presented at *IEEE Conference on Control Applications*, Dearborn, Michigan, September 15-18 1996.

[2] A. G. Kelkar and S. M. Joshi.

Trajectory tracking of multibody spacecraft.

Presented at *1996 International Mechanical Engineering Congress and Exposition*, Atlanta, GA, November 17-22 1996.

[3] A. G. Kelkar and S. M. Joshi.

Globally stable maneuvers of flexible space robots.

Presented at *Fourth International Conference on Control, Automation, Robotics, and Vision*, Westin Stamford, Singapore, December 3-6 1996.

[4] A. G. Kelkar and S. M. Joshi.

Robust control of non-passive systems via passification.

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[5] S. M. Joshi and A. G. Kelkar.

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[6] A. G. Kelkar and S. M. Joshi.

On passivity-based control of flexible multibody nonlinear systems.

Presented at *IEEE Conference on Decision and Control*, Hyatt Regency, San Diego, CA,, December 10-12 1997.

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[10] Y. Mao, A. G. Kelkar, and S. M. Joshi.

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